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**deVilliers et al.**

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(54) **EPITAXIAL DEVICES**

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(2013.01); **C30B 33/00** (2013.01); **H01L 21/0243** (2013.01); **H01L 21/0254** (2013.01); **H01L 21/02381** (2013.01); **H01L 21/02658** (2013.01); **H01L 21/3086** (2013.01); **H01L 33/30** (2013.01); **H01L 33/007** (2013.01)

(58) **Field of Classification Search**  
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See application file for complete search history.

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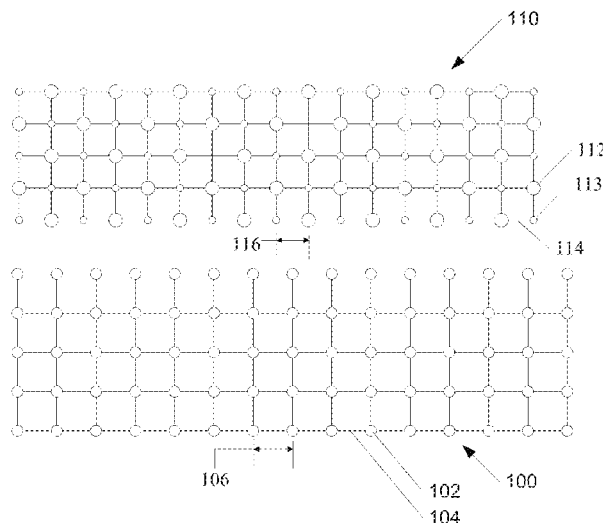
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(57) **ABSTRACT**

Epitaxial growth methods and devices are described that include a textured surface on a substrate. Geometry of the textured surface provides a reduced lattice mismatch between an epitaxial material and the substrate. Devices formed by the methods described exhibit better interfacial adhesion and lower defect density than devices formed without texture. Silicon substrates are shown with gallium nitride epitaxial growth and devices such as LEDs are formed within the gallium nitride.

**20 Claims, 10 Drawing Sheets**



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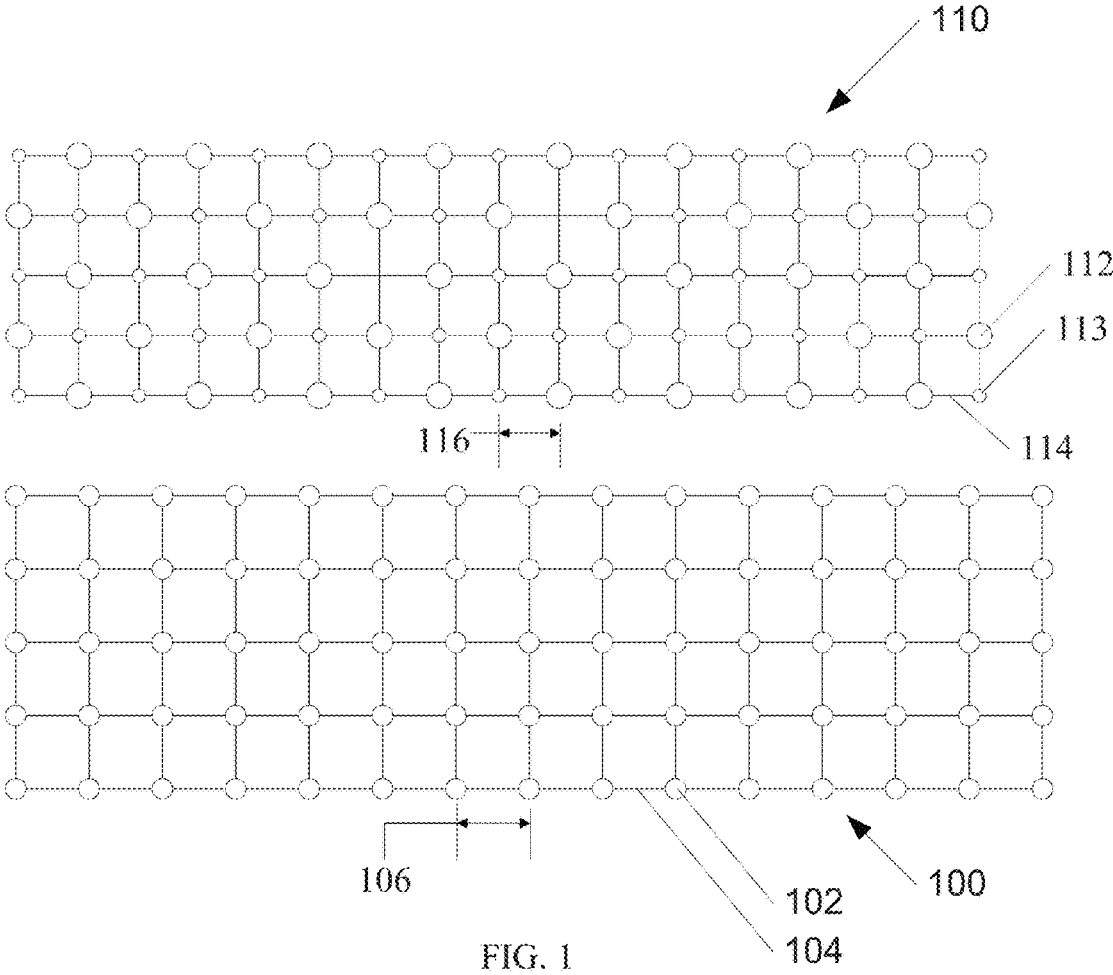
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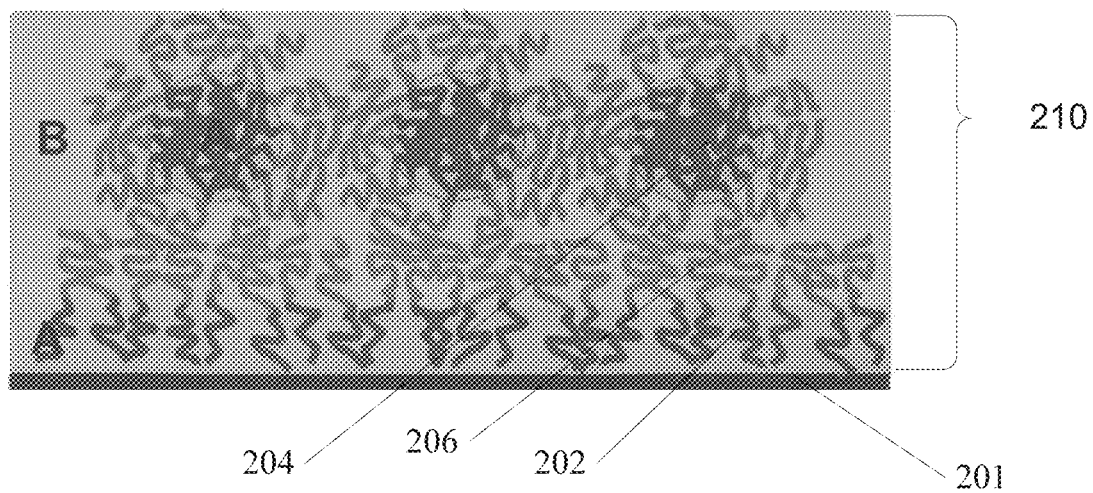
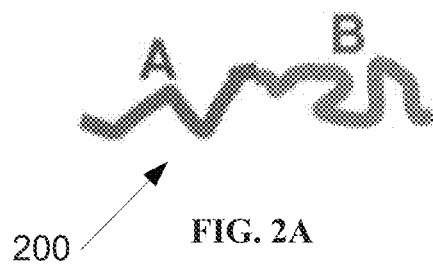
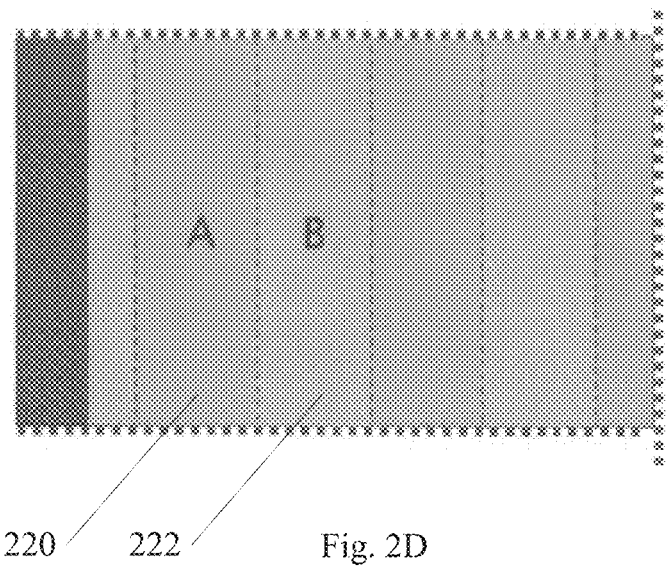
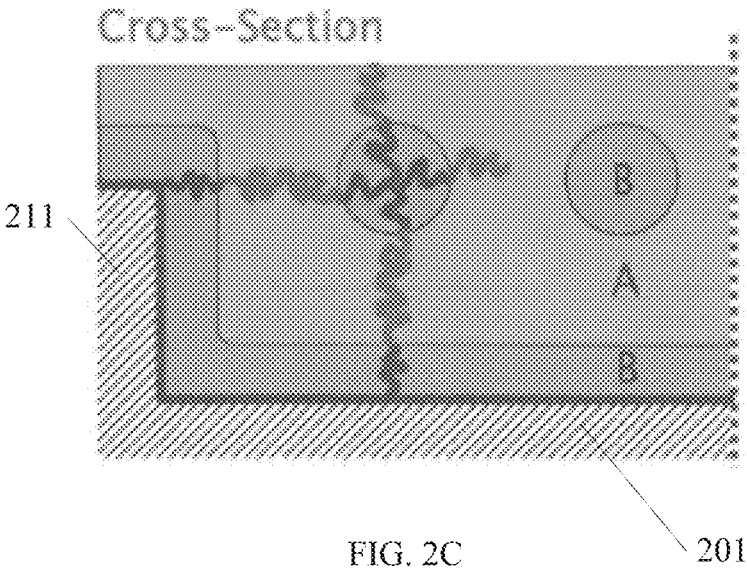


FIG. 2B



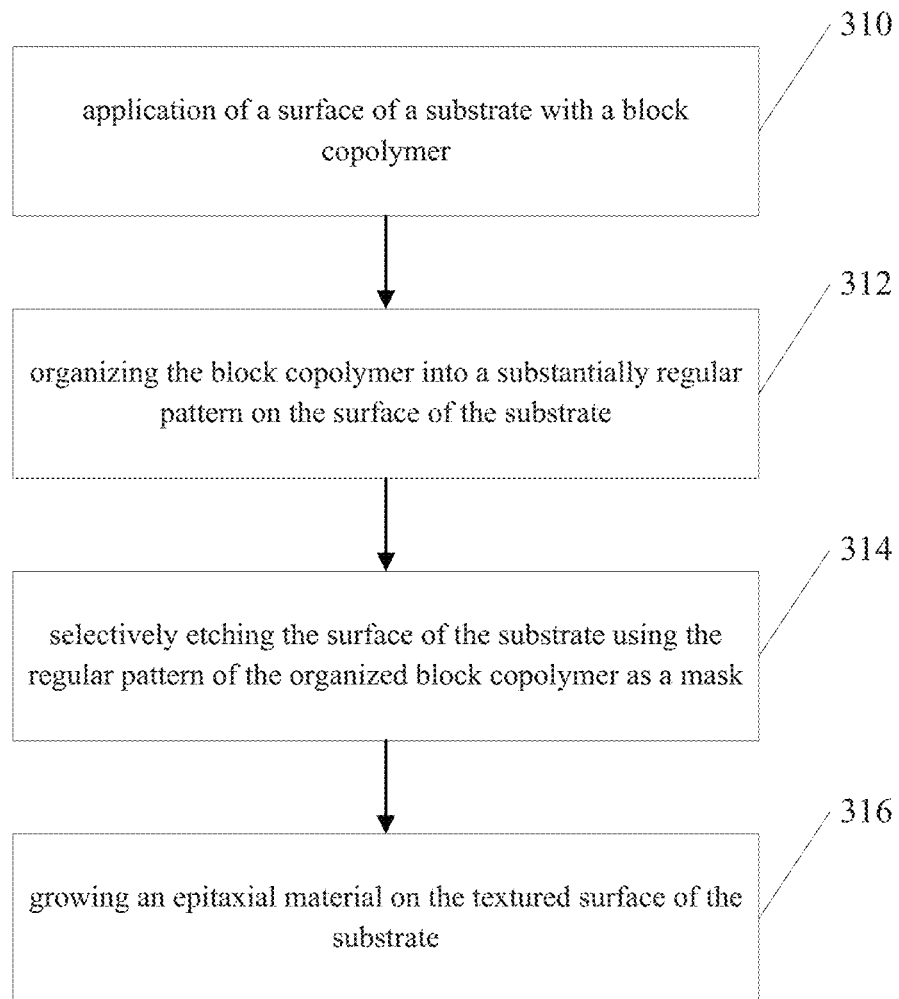


FIG. 3

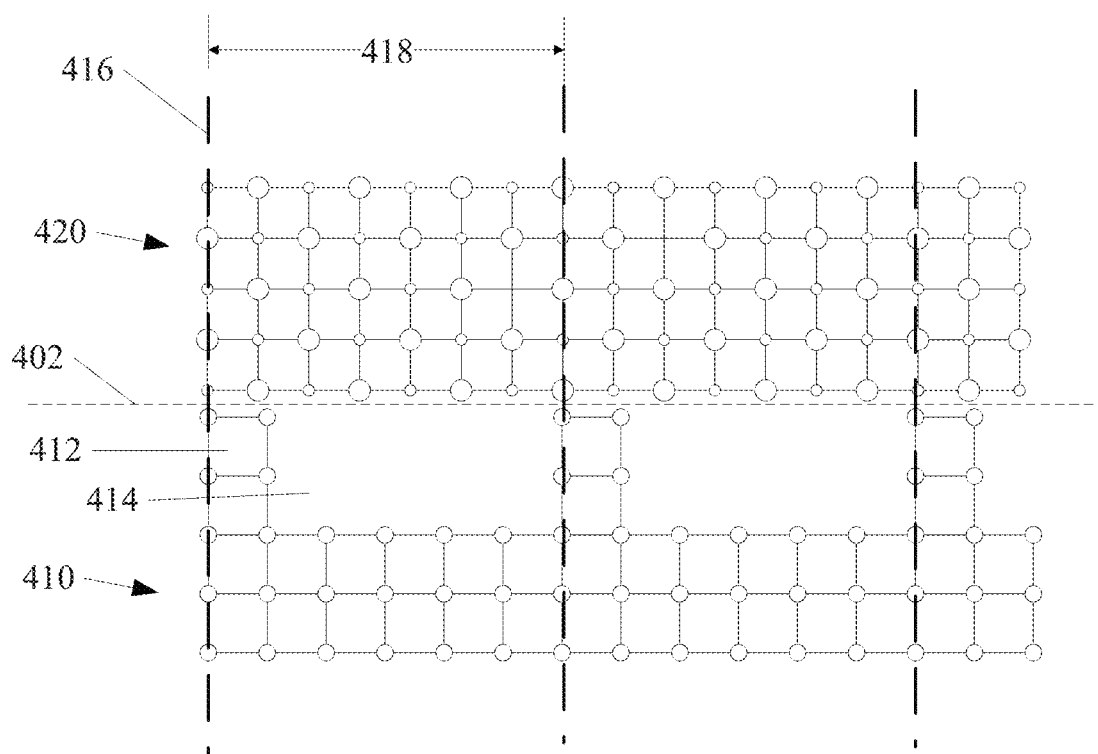


FIG. 4

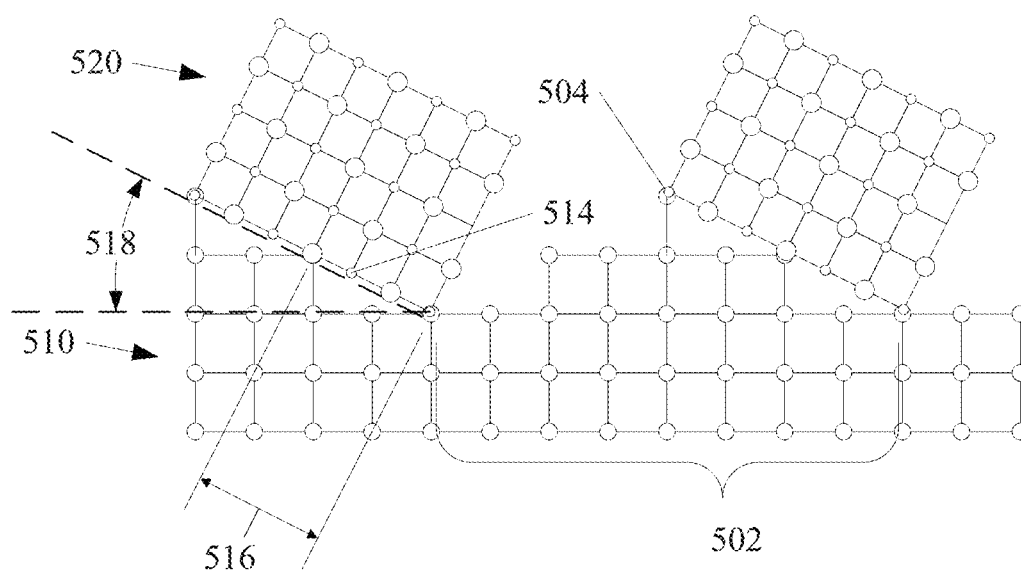
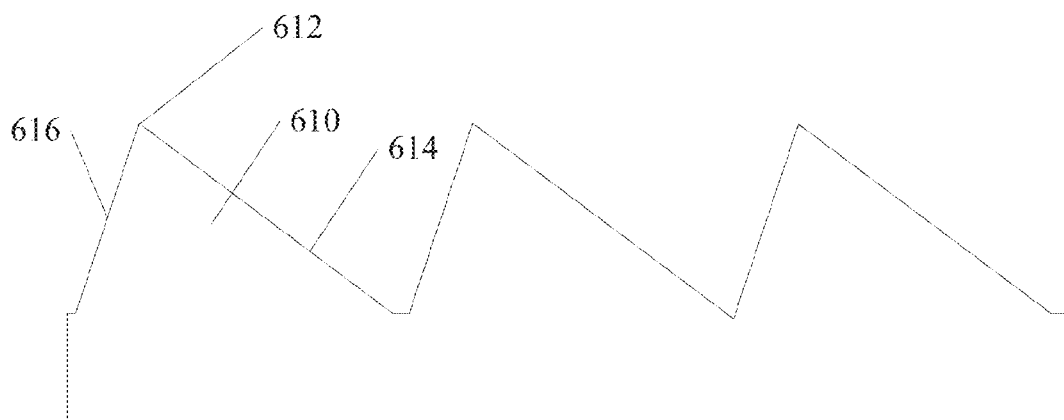


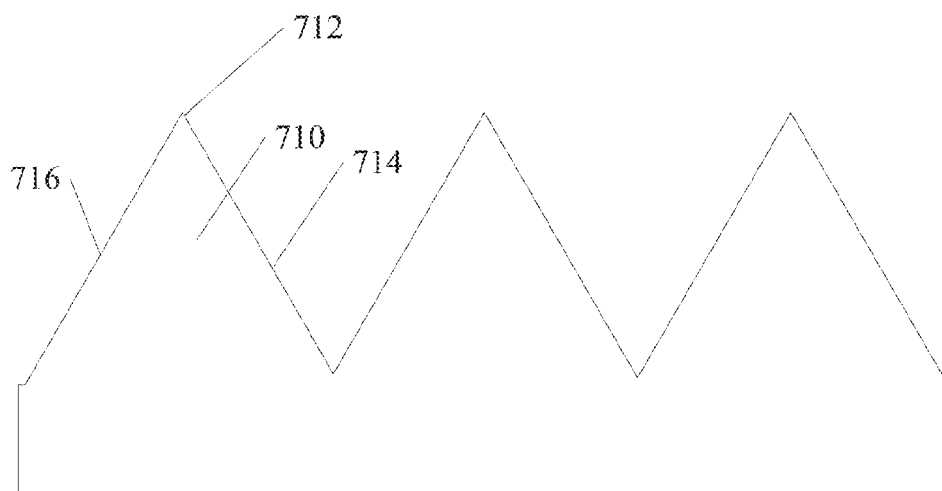
FIG. 5





600

FIG. 6



700

FIG. 7

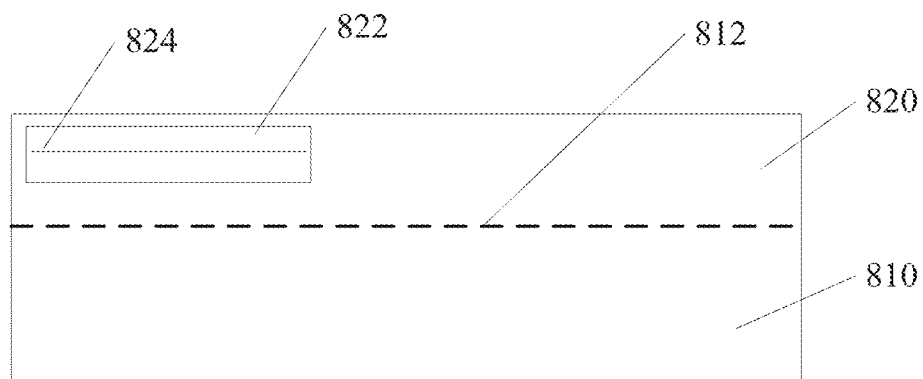


FIG. 8

800

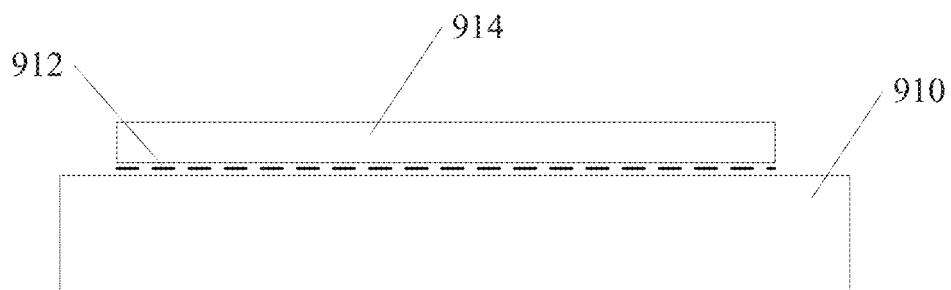


FIG. 9

900

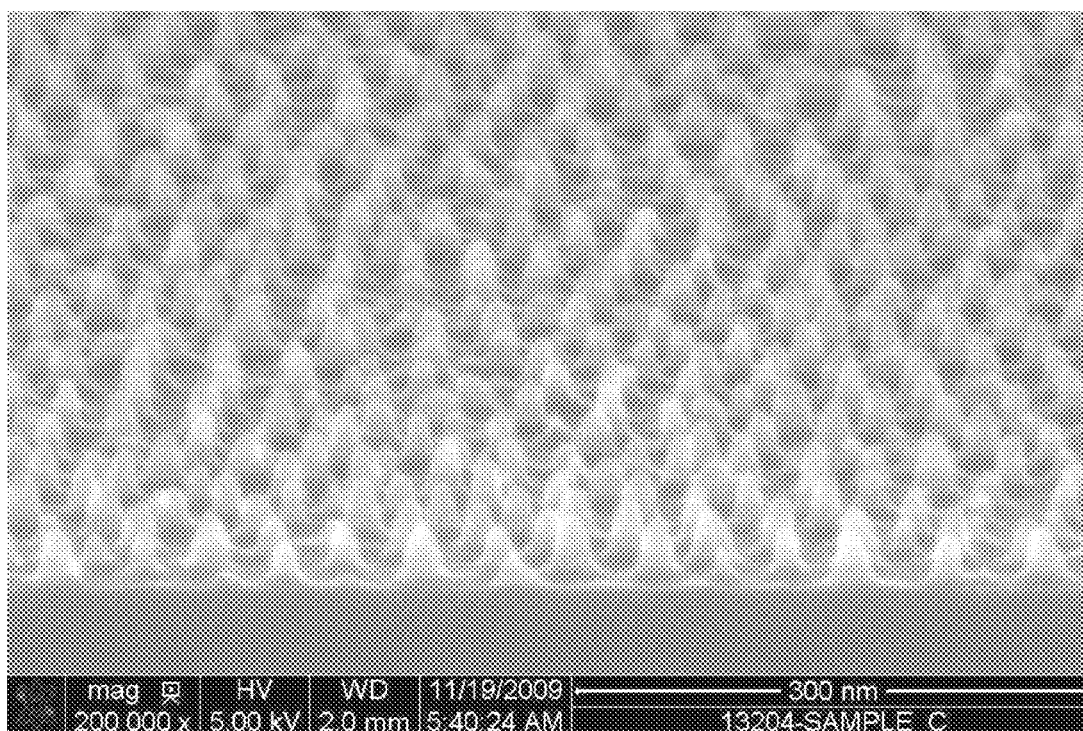


FIG. 10

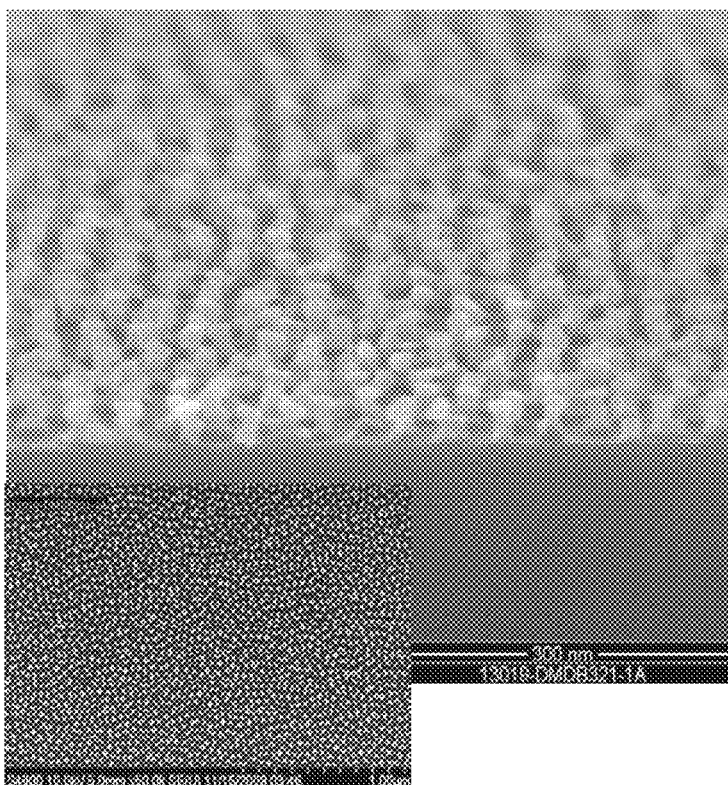


FIG. 11

## PRIORITY APPLICATION

This application is a divisional of U.S. application Ser. No. 13/901,767, filed May 24, 2013, which is a continuation of U.S. application Ser. No. 13/528,574, filed Jun. 20, 2012, now issued as U.S. Pat. No. 8,450,776, which is a divisional of U.S. application Ser. No. 12/826,275, filed Jun. 29, 2010, now issued as U.S. Pat. No. 8,216,943, both of which are incorporated herein by reference in their entirety.

## BACKGROUND

Many semiconductor devices, in particular Light Emitting Diode (LED) devices, utilize semiconductor materials other than silicon. These materials, such as gallium nitride (GaN), gallium arsenide (GaAs), gallium antimonide (GaSb) etc. can be expensive or even not available in a bulk material form. In order to utilize these materials in a cost efficient way, an epitaxial film of the desired semiconductor material is grown on a suitable substrate. However, growing a high quality epitaxial film, with low crystal defect density, is typically facilitated by using a substrate with a closely matching lattice constant.

Presently, sapphire (crystalline aluminum oxide) structures are used as substrates, but they are expensive, costing up to hundreds of dollars for a two inch wafer. It would be economically attractive, and would facilitate circuit integration, to manufacture devices such as LEDs or other semiconductor devices using a less expensive substrate material, such as silicon, to reduce production costs. However, direct epitaxial growth of GaN on a silicon surface tends to produce lower quality epitaxial films with higher defect densities, due to differing lattice constants.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows two different semiconductor materials according to an embodiment of the invention.

FIG. 2A shows an example block copolymer according to an embodiment of the invention.

FIG. 2B shows a portion of a substrate during a manufacturing process according to an embodiment of the invention.

FIG. 2C shows a portion of a substrate during a manufacturing process according to an embodiment of the invention.

FIG. 2D shows a top view of a substrate during a manufacturing process according to an embodiment of the invention.

FIG. 3 shows a flow diagram of an example method according to an embodiment of the invention.

FIG. 4 shows an interface between two semiconductor materials according to an embodiment of the invention.

FIG. 5 shows another interface between two semiconductor materials according to an embodiment of the invention.

FIG. 6 shows another interface between two semiconductor materials according to an embodiment of the invention.

FIG. 7 shows another interface between two semiconductor materials according to an embodiment of the invention.

FIG. 8 shows a semiconductor device according to an embodiment of the invention.

FIG. 9 shows another semiconductor device according to an embodiment of the invention.

FIG. 10 shows a micrograph of a semiconductor surface according to an embodiment of the invention.

FIG. 11 shows a micrograph of a semiconductor surface according to an embodiment of the invention.

In the following detailed description of the invention, reference is made to the accompanying drawings that form a part hereof and in which are shown, by way of illustration, specific embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and chemical, structural, logical, and electrical changes may be made.

The terms wafer and substrate used in the following description include any structure having an exposed surface with which to form a device or integrated circuit (IC) structure. The term substrate is understood to include semiconductor wafers. The term substrate is also used to refer to semiconductor structures during processing, and may include other structures, such as silicon-on-insulator (SOI), etc. that have been fabricated thereupon. Both wafer and substrate include doped and undoped semiconductors, epitaxial semiconductor structures supported by a base semiconductor or insulator, as well as other semiconductor structures well known to one skilled in the art. The term conductor is understood to include semiconductors, and the term insulator or dielectric is defined to include any material that is less electrically conductive than the materials referred to as conductors.

The term “horizontal” as used in this application is defined as a plane parallel to the conventional plane or surface of a wafer or substrate, regardless of the orientation of the wafer or substrate. The term “vertical” refers to a direction perpendicular to the horizontal as defined above. Prepositions, such as “on”, “side” (as in “sidewall”), “higher”, “lower”, “over” and “under” are defined with respect to the conventional plane or surface being on the top surface of the wafer or substrate, regardless of the orientation of the wafer or substrate. The following detailed description is, therefore, not to be taken in a limiting sense, and the scope of the present invention is defined only by the appended claims, along with the full scope of equivalents to which such claims are entitled.

FIG. 1 illustrates an example of a silicon lattice **100** and a gallium nitride lattice **110**. The silicon lattice **100** includes a regular, crystalline pattern of silicon atoms **102** spaced apart by bonds **104**. The silicon lattice constant is illustrated as distance **106**. The gallium nitride lattice **110** includes both gallium atoms **112** and nitrogen atoms **113** with bonds **114** arranged to form the lattice **110**. A gallium nitride lattice constant **116** is shown with a smaller lattice constant than the silicon lattice constant **106**. It is desired to have the atoms in the gallium nitride lattice **110** line up with the silicon atoms **102** in the silicon lattice **100**. When the lattice constants are different, the bonds tend to distort and create internal stresses in the materials, which can lead to unwanted defects such as dislocations, and can increase the likelihood of an unwanted fracture plane along the interface.

FIG. 2A illustrates a block copolymer molecule **200** that is used in a method that improves the interface between a substrate and an epitaxial material to reduce defects and improve strength at the interface. The block copolymer molecule **200** includes different polymer chains that are attached together. In its simplest form, as illustrated in FIG. 2A, the block copolymer includes two different polymer chains, A and B, coupled together. One of ordinary skill in the art will recognize that other, more complex block copolymers can also be used within the scope of the invention. Examples include multiple blocks such as tri-blocks, other multi-component blocks, branched copolymers, etc.

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FIG. 2B illustrates a substrate **201** with an assembled block copolymer **210**. The block copolymer **210** includes a first "A" region **202** assembled adjacent to the substrate **201** and a second "A" region **204** assembled at a distance away from the substrate **201** and separated from the first "A" region by a "B" region **206**. In the example illustrated in FIG. 2B, the second "A" region is shown assembled as islands in an array, e.g., either spherical micelles or surface-normal cylinders of material "A" within a matrix of material "B." Other assembly formations include rows, or similar energetically favorable configurations that segregate "A" regions apart from "B" regions.

Advantageously, in one example, the block copolymer **210** is a self-assembling coating. The "A" regions **202** arrange themselves apart from the "B" regions **206** by themselves when heated or otherwise activated. In one example, the substrate **201** is a silicon substrate, although other substrate materials such as germanium, gallium arsenide, etc. are also possible. Silicon substrates are readily available, and are useful to reduce cost of the resulting semiconductor device.

FIG. 2C illustrates the substrate **201**, having an added geometric feature **210** in the substrate topography. In one example features **211**, such as the sidewall shown in FIG. 2C, are etched into the substrate **201** prior to adding the block copolymer **210**. As shown in FIG. 2C, in selected examples, the feature **211** is used to direct assembly of the block copolymer **210** by providing a guiding surface out of the horizontal plane of the substrate **201**.

FIG. 2D illustrates an example of a top view of a self assembled block copolymer on a surface of the substrate **201**. In the example shown, the block copolymer regions "A" and "B" are assembled into rows. As noted above, other examples of assembled patterns include, but are not limited to arrays of islands or grids.

In one example, block copolymers **210** and their assembled regular pattern are used to selectively etch the substrate **201**. One example method of using block copolymers, as described above, to selectively etch and further form an epitaxial material on a substrate surface is shown in FIG. 3.

A block copolymer coating is deposited on a surface of a substrate in operation **310**. In operation **312**, the block copolymer coating organizes into a substantially regular pattern. Process conditions such as elevated temperature, time, a solvent anneal, etc. can be used to organize the block copolymer.

In operation **314**, using polymer chemistry, or adding a dopant to "A" or "B" regions, etc., either the "A" region or the "B" region is selectively removed from the surface of the substrate, and the remaining region of the block copolymer coating is used as a mask in a subsequent etch process. A resulting textured surface is formed in the substrate. The textured surface corresponds to the regular pattern of the block copolymer coating, although it may not be identical. Depending on process conditions such as etchant chemistry, etch duration, etc., the textured surface may include pits, holes, or trenches with vertical sidewalls, angled sidewalls, or other geometries.

In operation **316**, an epitaxial material is grown on the textured surface of the substrate. In one example specific geometries of the textured surface are used to promote high quality epitaxial material growth as will be discussed in more detail below.

Using block copolymers to mask and etch a substrate surface provides advantages, in contrast to other techniques such as optical lithography. The added process steps of forming an optical mask and exposing, developing, stripping, etc. of resist materials add cost to the manufacturing process. Using

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self-assembled block copolymers as an etch mask saves manufacturing steps. In addition, block copolymers are effective at forming nanometer scale textured surfaces on semiconductor substrates, at dimensions smaller than what is attainable with conventional photolithography.

FIG. 4 illustrates one possible mechanism of textured surface geometry promoting high quality epitaxial material growth. A substrate lattice **410** such as silicon, is etched to form a surface texture using selected block copolymer methods described above. FIG. 4 illustrates a textured surface having a geometry that includes a number of islands **412** and a number of spaces **414** between the islands. In one example, a periodicity **418** of the islands **412** is selected to substantially reduce a lattice mismatch between the patterned substrate **410** and an epitaxial material **420**.

As can be seen in FIG. 4, the atoms in the epitaxial material **420** do not match one to one with the atoms in the substrate **410**, however the periodicity **418** helps align atoms at a particular interval to better reduce a lattice mismatch between the substrate **410** and the epitaxial material **420**. Lines **416** shown in FIG. 4 illustrate how the atoms in contact at an interface **402**, are substantially aligned. In one example, the periodicity **418** is selected to correspond to approximately  $\pm 25\%$  of an integer multiple of the lattice constant of the epitaxial material **420**.

FIG. 5 illustrates another possible mechanism of textured surface geometry promoting high quality epitaxial material growth. A number of features **502** are etched into a surface of a substrate **510**, using selected block copolymer methods described above. FIG. 5 is shown in cross section, so the three dimensional detail of the features **502** is not shown. Examples of features **502** include pyramids such as four-sided pyramids, or other numbers of sides, based on crystal structure of the substrate **510**. Other examples of features **502** include conical shapes, with angled sides as shown. In other examples, the features **502** include rows with a cross section as shown in FIG. 5, the rows having angled sides. The features **502** form an apex **504** with angled surfaces **514** extending away from the apex **504**. The angle **518** of the angled surfaces **514** is illustrated with respect to an average surface plane of the substrate **510**.

The angled surfaces **514** create a modified lattice spacing **516** which substantially corresponds to a lattice spacing of alternate crystal planes in the substrate **510**. The Figure illustrates how a properly chosen angle **518** results in a spacing **516** that substantially corresponds to a lattice spacing of an epitaxial material **520**. The Figure further illustrates how a number of epitaxial material portions **520** are formed on angled surfaces of the substrate.

As epitaxial growth progresses, the multiple epitaxial material portions **520** will form together and create a substantially homogenous epitaxial material. Using the angled surfaces as shown, the interface between the substrate **510** and the epitaxial material includes improved lattice matching, and as a result decreases lattice defects in the epitaxial material and improves adhesion at the interface. Although only one angled surface **514** is shown with epitaxial growth for illustration, one of ordinary skill in the art will recognize that other angled surfaces will also include epitaxial growth. Additionally, although atomic scale is shown in the Figure for illustration, one of ordinary skill in the art will recognize that scale of features **502** and angled surfaces **514** in practice may be much larger.

FIG. 6 illustrates another example of angled surfaces **614** on a substrate **610** with the atomic detail removed. In FIG. 6, one embodiment is illustrated that includes asymmetric angled surfaces with respect to apex **612**. For example the

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surface **614** is shown at a more acute angle than surface **616**, with respect to a horizontal plane of the substrate **610**.

FIG. 7 illustrates another example of angled surfaces **700** on a substrate **710**. Similar to the example illustrated in FIG. 5, in FIG. 7, the angled surfaces are symmetric with respect to apex **712**. The surface **714** is shown at a substantially the same angle as surface **716**, with respect to a horizontal plane of the substrate **710**.

FIG. 8 illustrates an example of a semiconductor device **800** formed using methods of patterning and texturing as described above. FIG. 8 shows a semiconductor substrate **810** with an epitaxial material **820** formed over the substrate **810**. An interface **812** is shown between the substrate **810** and the epitaxial material **820**. In one embodiment, the interface **812** is formed using block copolymer masking, as described above, to form a texture in the substrate. The texture facilitates improved quality and reduction in defects in the epitaxial material **820** as described above.

In one example the substrate **810** includes a silicon substrate. In one example the epitaxial material **820** includes a gallium nitride epitaxial material. One particular semiconductor device **800** that can be formed using methods described in the present disclosure includes an LED device. Gallium nitride is a useful material to form LEDs with selected wavelengths of light. FIG. 8 illustrates an LED **822** in block diagram form. A P-N junction **824** is illustrated as a functioning component of the LED **822**. One of ordinary skill in the art, having the benefit of the present disclosure will recognize that any of a number of different geometries and circuit designs for LED **822** may be possible. The ability to form high quality epitaxial gallium nitride on silicon increases the quality of the LED semiconductor device **800** and reduces the cost.

FIG. 9 illustrates another example of a semiconductor device **900** formed using methods of patterning and texturing as described above. FIG. 9 shows a semiconductor substrate **910** with a textured surface **912** formed over at least a portion of the substrate **910**. A liquid crystal media **914** is shown in contact with the textured surface **912** on the substrate **910**. Examples of semiconductor devices **900** include liquid crystal displays. Using the cost effective methods of forming a texture on a substrate, as described above, a liquid crystal media performance is enhanced. In one example the textured surface facilitates improved organization of the liquid crystal media in response to an applied electric field. In other examples, a semiconductor substrate **910** with a textured surface **912** is used as a template in a manufacturing process of a liquid crystal device, in contrast to using the semiconductor substrate **910** directly with a liquid crystal media.

FIG. 10 shows a micrograph of a textured silicon surface formed using block copolymer masking as described in various embodiments above. Individual islands are shown having angled surfaces. FIG. 11 shows another micrograph of a textured silicon surface formed using block copolymer masking as described in various embodiments above. Embodiments such as shown in FIG. 11 can provide additional mechanical interlocking at an interface with an epitaxially grown material due to the enlarged heads of the islands formed.

While a number of embodiments of the invention are described, the above lists are not intended to be exhaustive. Although specific embodiments have been illustrated and described herein, it will be appreciated by those of ordinary skill in the art that any arrangement that is calculated to achieve the same purpose may be substituted for the specific embodiment shown. This application is intended to cover any adaptations or variations of the present invention. It is to be understood that the above description is intended to be illus-

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trative and not restrictive. Combinations of the above embodiments, and other embodiments, will be apparent to those of skill in the art upon studying the above description.

What is claimed is:

1. A light emitting diode, comprising:
  - a silicon substrate;
  - one or more angled surfaces formed on the silicon substrate;
  - epitaxial gallium nitride formed on the one or more angled surfaces; and
  - a P-N junction located in the epitaxial gallium nitride to provide light as electrons combine with holes across the P-N junction.
2. The light emitting diode of claim 1, wherein the one or more angled surfaces includes an array of angled surfaces.
3. The light emitting diode of claim 1, wherein the one or more angled surfaces are asymmetric.
4. The light emitting diode of claim 2, wherein the array of angled surfaces are included in an array of pyramid shaped structures.
5. The light emitting diode of claim 2, wherein the array of angled surfaces are included in an array of conical shaped structures.
6. The light emitting diode of claim 1, wherein the one or more angled surfaces are positioned between approximately 10 and 15 degrees with respect to a surface plane of the substrate.
7. A light emitting diode, comprising:
  - a silicon substrate;
  - one or more angled surfaces formed on the silicon substrate;
  - epitaxial gallium arsenide formed on the one or more angled surfaces; and
  - a P-N junction located in the epitaxial gallium arsenide to provide light as electrons combine with holes across the P-N junction.
8. The light emitting diode of claim 7, wherein the one or more angled surfaces includes a number of periodically repeating angled surfaces with a surface normal vector that is between 0 degrees and 90 degrees with respect to a plane of the surface of the substrate.
9. The light emitting diode of claim 7, wherein the one or more angled surfaces includes a number of linear structures.
10. The light emitting diode of claim 9, wherein the one or more angled surfaces are asymmetric.
11. The light emitting diode of claim 7, wherein the one or more angled surfaces are included in an array of pyramid shaped structures.
12. The light emitting diode of claim 7, wherein the one or more angled surfaces are included in an array of conical shaped structures.
13. The light emitting diode of claim 7, wherein the one or more angled surfaces are positioned between approximately 10 and 15 degrees with respect to a surface plane of the substrate.
14. A light emitting diode, comprising:
  - a silicon substrate;
  - one or more angled surfaces formed on the silicon substrate;
  - epitaxial gallium antimonide formed on the one or more angled surfaces; and
  - a P-N junction located in the epitaxial gallium antimonide to provide light as electrons combine with holes across the P-N junction.
15. The light emitting diode of claim 12, wherein the one or more angled surfaces includes an array of island texture features.

**16.** The light emitting diode of claim **13**, wherein the array of island texture features includes angled surfaces that are asymmetric.

**17.** The light emitting diode of claim **13**, wherein the array of island texture features includes pyramid shaped structures. 5

**18.** The light emitting diode of claim **13**, wherein the array of island texture features includes conical shaped structures.

**19.** The light emitting diode of claim **1**, wherein the one or more angled surfaces are positioned between approximately 10 and 15 degrees with respect to a surface plane of the 10 substrate.

**20.** A light emitting diode, comprising:

a silicon substrate;

one or more angled surfaces formed on the silicon substrate; 15

an epitaxial material formed on the one or more angled surfaces, the epitaxial material having a lattice constant that is different from the substrate; and

a P-N junction located in the epitaxial material to provide light as electrons combine with holes across the P-N 20 junction.

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